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An aeroacoustic study of a leading-edge slat: Beamforming and far field estimation using near field quantities

Kyle A. Pascioni *, Louis N. Cattafesta

Florida Center for Advanced Aero-Propulsion, Department of Mechanical Engineering, Florida State University, Tallahassee, FL, USA

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ABSTRACT

The leading edge slat of a high-lift system is a large contributor to the overall radiated acoustic field from an aircraft during the approach phase of the flight path. This is due to the unsteady flow field generated in the slat-cove and near the leading edge of the main element. In an effort to understand the noise-source mechanisms, a suite of experimental measurements has been performed on a two-dimensional multi-element MD-30P30N airfoil, including PIV, steady and unsteady surface pressure, and phased microphone array measurements. Acoustic trends are given with angle of attack and flow speed which corresponds to a stowed chord Reynolds number range of $1.2 \times 10^6 \le Re_c \le 1.71 \times 10^6$. Spatially integrated beamforming is used to isolate the slat noise, while Kevlar sidewalls are utilized to minimize environmental influence. In addition, temporally-resolved estimates of a low-dimensional representation of the velocity vector fields are obtained through the use of proper orthogonal decomposition and spectral linear stochastic estimation and show good agreement with independent phase-locked PIV measurements. A time-resolved estimate of the pressure field is then computed via solution of the pressure Poisson equation. From this, Curle's acoustic analogy scaled for the frequency-dependent spanwise coherence length projects the time-resolved pressure forces in the slat region to the acoustic far field for comparison to the array measurements. The favorable results establish the connection between the dominant unsteady flow structures most responsible for the radiated noise and provide insight for future noise reduction efforts.

1. Introduction

Alongside performance and emissions, noise pollution is a major concern that must be addressed in order to sustain the commercial airline industry. An approaching aircraft typically has one or more high-lift devices deployed in addition to the landing gear. These geometric modifications relative to the cruise configuration generate several unsteady flow processes. For example, the bluff shape of the landing gear induces an unsteady wake that generates low-frequency noise superimposed with high-frequency content due to small geometric features [1]. Unequal pressure loading at the side of a trailing edge flap generates a double vortex structure that produces an intense source of sound [2]. Medium-to-large commercial transports are also equipped with a leading-edge slat to provide higher lift and decrease the stall speed. Unfortunately, current designs optimized for aerodynamic capabilities are accompanied by a complex flow field with characteristics that are dependent on flow conditions and geometry. Slats typically span most of the wing; therefore, they represent a distributed noise source that can dominate the

* Corresponding author. National Institute of Aerospace, Hampton, VA, USA.
E-mail address: kyle.pascioni@nianet.org (K.A. Pascioni).

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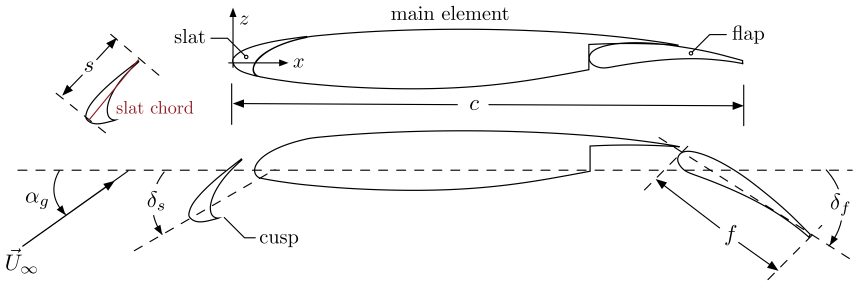

Fig. 1. Airfoil section geometry of the 30P30N high-lift configuration defining nomenclature. The reader is referred to [34] for geometric constraints not explicitly shown in the figure above. Note the coordinate system origin is at the leading edge of the stowed airfoil.

airframe noise signature [3]. This work will focus specifically on the leading-edge slat and attempt to link hydrodynamic phenomena with the acoustic far field to better understand the noise generation processes.

In general, the slat flow field has a large separated region due to the geometric cove that allows the slat to retract onto the main wing during cruise (see Fig. 1). As the flow accelerates and passes the slat cusp, a shear layer develops between the low-speed cove flow and higher-speed flow that eventually exits through the slat-main element gap. A Kelvin-Helmholtz instability develops in the initial shear layer which grows into coherent structures. For most angles of attack, these coherent structures impinge on the slat underside, resulting in an unsteady reattachment position. [4] found that large streamwise-oriented vortices and hairpin vortical structures are visible at the impingement location. Vortical structures are then pushed through the slat-main element gap or trapped in the recirculating cove. The vortices that pass through the gap first experience regions of high strain by the mean flow forcing them to stretch and distort in an unsteady fashion, each sending pressure waves which likely produce a portion of the broadband noise component in the process [5]. Additionally [6], give evidence that a significant part of the acoustic energy is due to vortical structures interacting with the slat trailing edge by being scattered into pressure waves.

Trailing edge vortex shedding has also been identified as a high-frequency phenomena [7]. Typically, a high-frequency hump or more narrow peak is observed, scaling with the local flow speed and trailing edge thickness. As angle of attack is increased, the proximity of the cove shear layer reattachment point to the trailing edge can affect the vortex shedding process. At low angles where the reattachment point is close to the trailing edge, the interaction/disruption of organized shedding is more substantial. Conversely, high angles allow the cove flow and trailing edge flow to persist in a rather independent fashion.

Narrowband pressure fluctuations are also observed during scaled experiments and low Reynolds number simulations which have been linked to a flow-acoustic interaction similar to Rossiter tones [8]. This resonance-like behavior is a byproduct of coherent shear layer structures impinging on the slat underside, where the corresponding frequencies can be accurately predicted using a modified Rossiter equation tailored to slat-cove physics [4]. At the present time, it is unclear what flow features are most important to consider for noise reduction, not to mention their variation with Reynolds number, Mach number, angle of attack, and geometry (e.g., including the effects of wing sweep not addressed here).

Recent acoustic measurements have employed array-based techniques for full-scale flyover [9,10] or scaled wind tunnel experiments [11–13]. The former are frequently used to rank source levels between airframe components, i.e., slat, flap, landing gear, etc. Wind tunnel experiments have the advantage of a controlled environment allowing cleaner extraction of trends. For example, these studies just mentioned have established sound pressure level scaling corresponding to a Mach power between four and five, which is consistent with theory [14].

Wind tunnel configurations for high-lift studies typically have either an open-jet test or a closed-wall test section. The boundary conditions imposed by an open-jet modify the airfoil surface pressure distribution such that a large geometric angle of attack correction is necessary. While successful open-jet high-lift experiments have been performed [15,16], solid blockage can limit the angles that produce the desired aerodynamic loading, making it unsuitable for smaller-scale facilities. Another disadvantage arises due to the deflection of the main tunnel jet by the airfoil's lift reaction force. The jet is directed away from the collector and produces recirculation in the anechoic chamber. Corruption of the microphone signals is evident, as well as an increase in effective background noise levels. One way to alleviate these adverse effects is to bound the tunnel jet in some manner. This has prompted many experiments to accept the reverberant environment of a closed-wall test section. However, it is difficult to obtain accurate source levels in close proximity to sound-hard boundaries. The chosen solution for the present work utilizes the optional closed-wall test section retrofitted with tensioned Kevlar sidewalls, similar to [17] and subsequently [18]. In an ideal sense, these walls bound the flow to simulate conventional aerodynamic facilities and have proven to be capable of matching the mean flow field of a free-air configuration. The motivation for using Kevlar walls lies in the ability to obtain desirable aerodynamic characteristics while also allowing the propagating acoustic waves to pass with little influence (acoustic loss corrections will be briefly detailed in the following sections).

While the benefits of a Kevlar test section will be leveraged with this work to gather acoustic measurements, the ultimate goal is to link the far field observations to specific flow phenomena to better understand the various source characteristics. One way to do so is to compute the pressure field from particle image velocimetry (PIV) vector fields using methods described by Refs. [19] and [20]. In doing so, Curle's analogy [21] can project the fluctuating pressure along the airfoil surface, and details of the